بسم الله الرحمن الرحيم

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Undergraduate Course

Solar Cells Fundamental

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Lecture (5)

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Solar Energy

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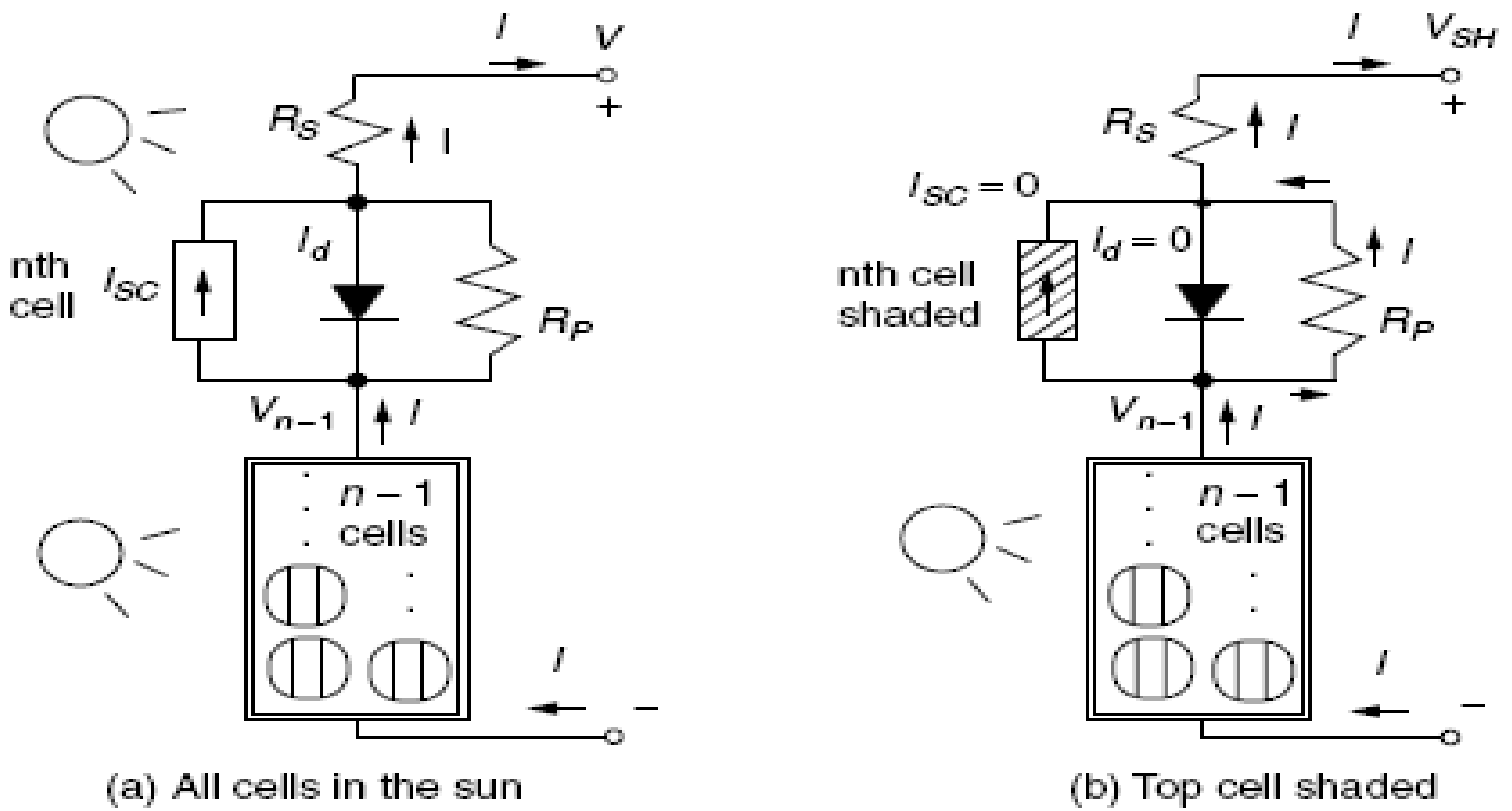
SHADING IMPACTS ON I –V CURVES

- The output of a PV module can be reduced dramatically when even a small portion of it is shaded.
- Unless special efforts are made to compensate for shade problems, even a single shaded cell in a long string of cells can easily cut output power by more than half.
- External diodes, purposely added by the PV manufacturer or by the system designer, can help preserve the performance of PV modules.
- The main purpose for such diodes is to mitigate the impacts of shading on PV *I –V* curves. Such diodes are usually added in parallel with modules or blocks of cells within a module.

Physics of Shading

To help understand this important shading phenomenon, consider the following figure in which an *n*-cell module with current *I* and output voltage *V* shows one cell separated from the others (shown as the top cell, though it can be any cell in the string). The equivalent circuit of the top cell has been drawn using the exact PV model, while the other ($n - 1$) cells in the string are shown as just a module with current *I* and output voltage V_{n-1}.

Physics of Shading



A module with *n* cells in which the top cell is in the sun (a) or in the shade (b).

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Physics of Shading

- In figure a, all of the cells are in the sun and since they are in series, the same current I flows through each of them.
- In figure b, however, the top cell is shaded and its current source I_{SC} has been reduced to zero. The voltage drop across R_P as current flows through it causes the diode to be reverse biased, so the diode current is also (essentially) zero. That means the entire current flowing through the module must travel through both R_P and R_S in the shaded cell on its way to the load. That means the top cell, instead of adding to the output voltage, actually reduces it.
- Consider the case when the bottom $n - 1$ cells still have full sun and still some how carry their original current I so they will still produce their original voltage V_{n-1}. This means that the output voltage of the entire module V_{SH} with one cell shaded will drop to

Physics of Shading

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$$V_{SH} = V_{n-1} - I\,(R_P + R_S)$$

With all n cells in the sun and carrying I , the output voltage was V so the voltage of the bottom $n - 1$ cells will be

$$V_{n-1} = \left(\frac{n-1}{n}\right) V$$

Combining both equations

$$V_{SH} = \left(\frac{n-1}{n}\right) V - I(R_P + R_S)$$

Physics of Shading

The drop in voltage ΔV at any given current *I* , caused by the shaded cell, is given by

$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right)V + I(R_P + R_S)$$

$$\Delta V = \frac{V}{n} + I(R_P + R_S)$$

Since the parallel resistance R_P is so much greater than the series resistance R_S , The ΔV equation can be simplified to

$$\Delta V \cong \frac{V}{n} + I R_P$$

At any given current, the *I* –*V* curve for the module with one shaded cell drops by ΔV. The huge impact this can have is illustrated in the following figure.

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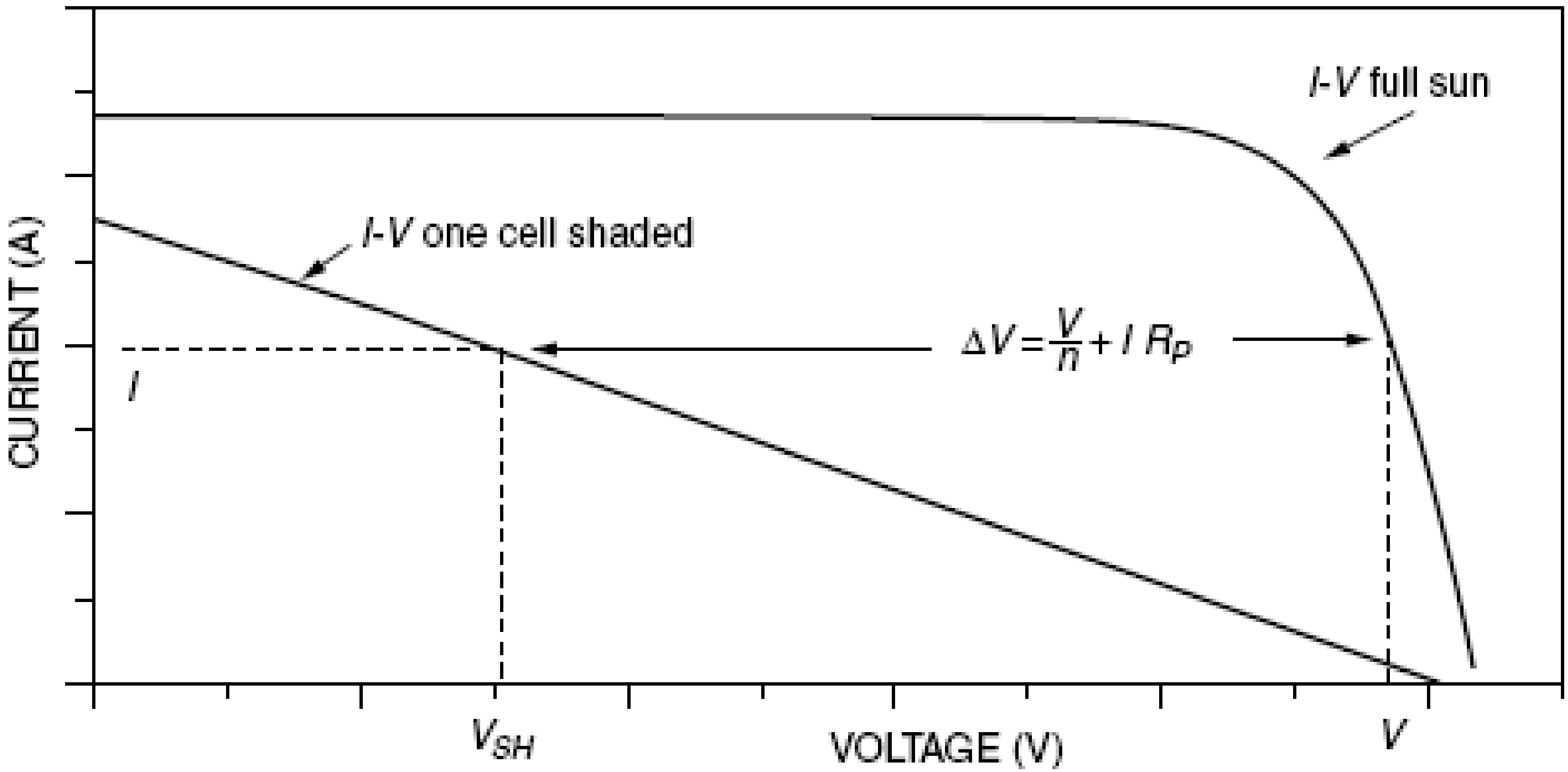
Physics of Shading



Effect of shading one cell in an *n*-cell module. At any given current, module voltage drops from V to $V - \Delta V$.

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Example

Impacts of Shading on a PV Module. The 36-cell PV module described in Example 8.4 had a parallel resistance per cell of $R_P = 6.6$. In full sun and at current $I = 2.14$ A the output voltage was found there to be $V = 19.41$ V. If one cell is shaded and this current somehow stays the same, then:

a. What would be the new module output voltage and power?

b. What would be the voltage drop across the shaded cell?

c. How much power would be dissipated in the shaded cell?

Solution.

a. The drop in module voltage will be

$$\Delta V = \frac{V}{n} + I R_P = \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

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Example

The new output voltage will be 19.41 − 14.66 = 4.75 V.
Power delivered by the module with one cell shaded would be
$P_{module} = V\,I = 4.75\text{ V} \times 2.14\text{ A} = 10.1\text{ W}$
For comparison, in full sun the module was producing 41.5 W.

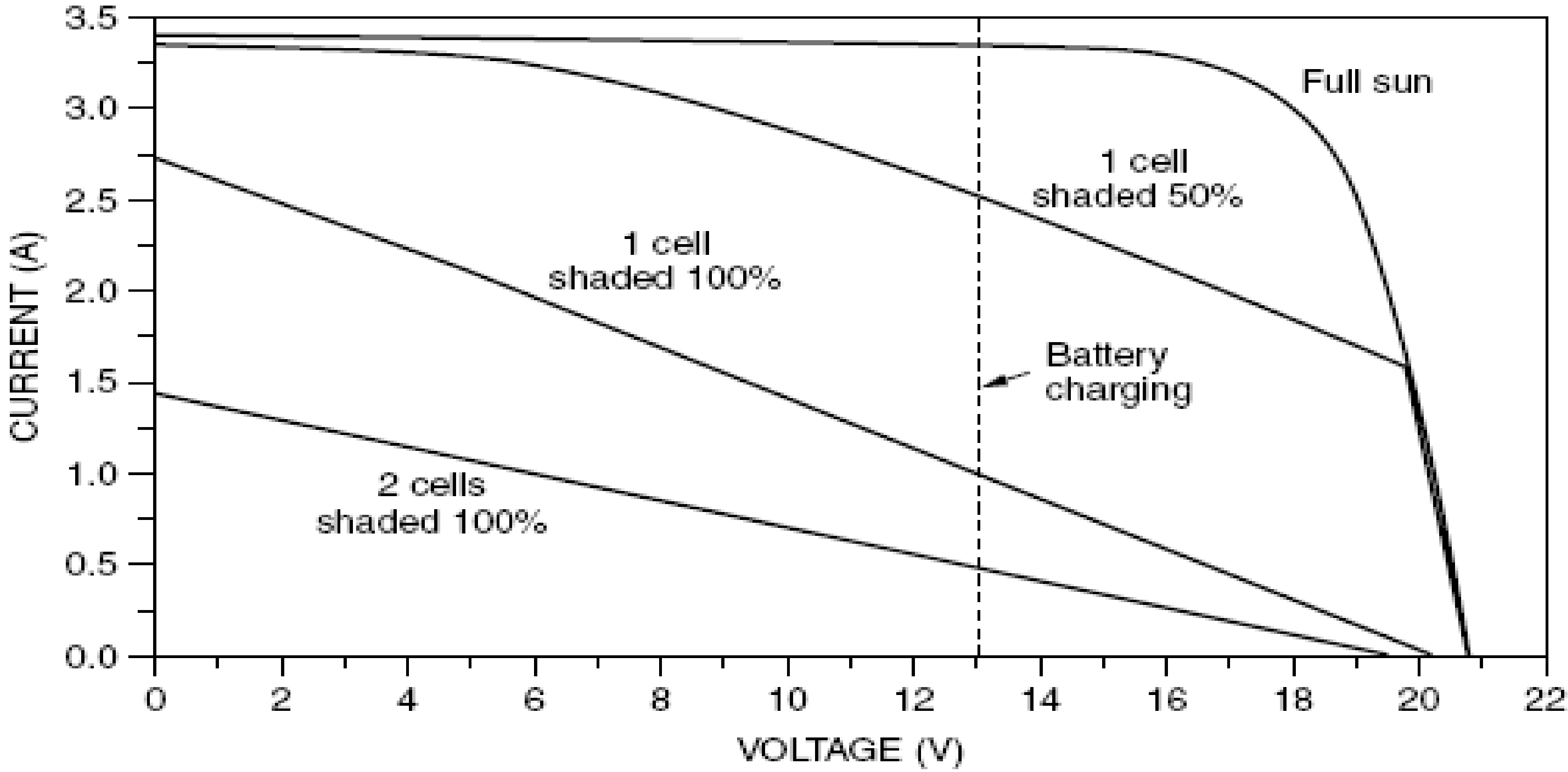
b. All of that 2.14 A of current goes through the parallel plus series resistance (0.005) of the shaded cell, so the drop across the shaded cell will be
$Vc = I\,(RP + RS) = 2.14(6.6 + 0.005) = 14.14\ V$
(normally a cell in the sun will add about 0.5 V to the module; this shaded cell subtracts over 14 V from the module).

c. The power dissipated in the shaded cell is voltage drop times current, which is $P = V_c I = 14.14\text{ V} \times 2.14\text{ A} = 30.2\text{ W}$
All of that power dissipated in the shaded cell is converted to heat, which can cause a local hot spot that may permanently damage the plastic laminates enclosing the cell.

Example

The following figure shows I – V curves for the example module under full-sun conditions and with one cell 50% shaded, one cell completely shaded, and two cells completely shaded. Also shown on the graph is a dashed vertical line at 13 V, which is a typical operating voltage for a module charging a 12-V battery. The reduction in charging current for even modest amounts of shading is severe. With just one cell shaded out of 36 in the module, the power delivered to the battery is decreased by about two-thirds!

Example



Effects of shading on the *I* –*V* curves for a PV module. The dashed line shows a typical voltage that the module would operate at when charging a 12-V battery; the impact on charging current is obviously severe.

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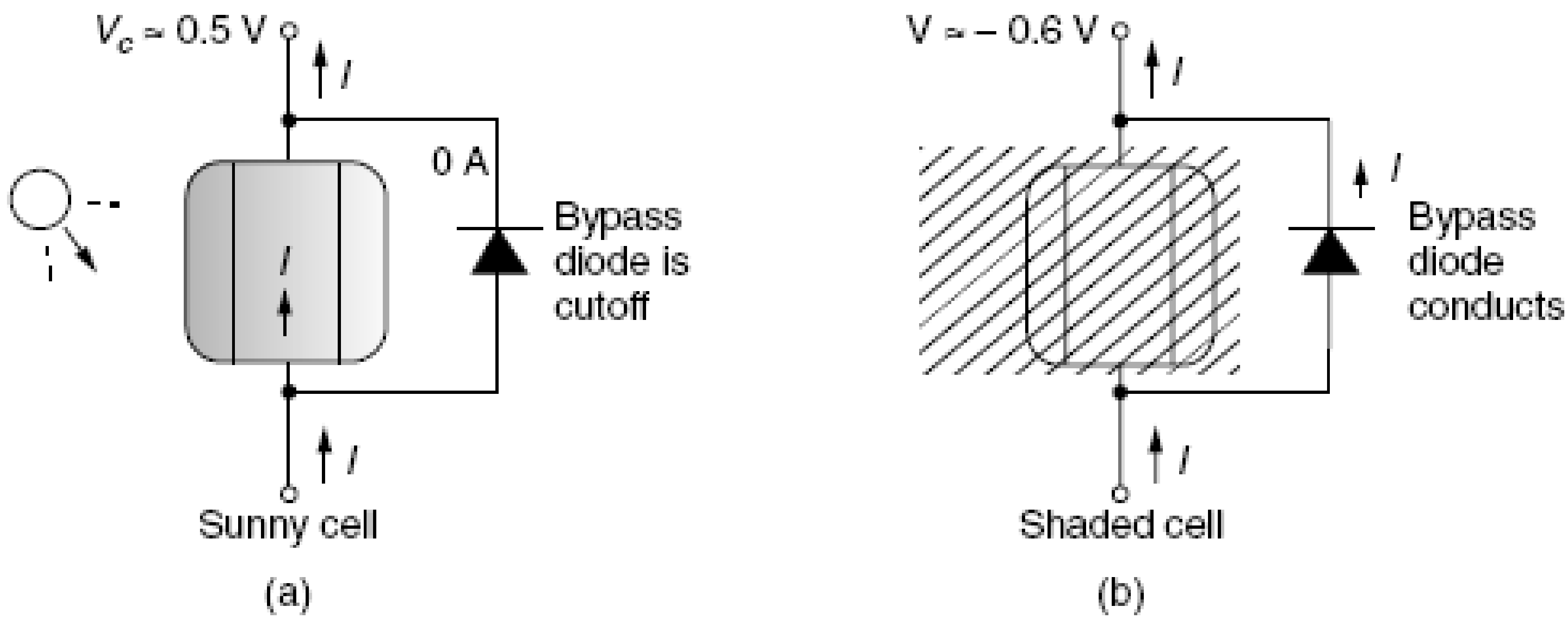
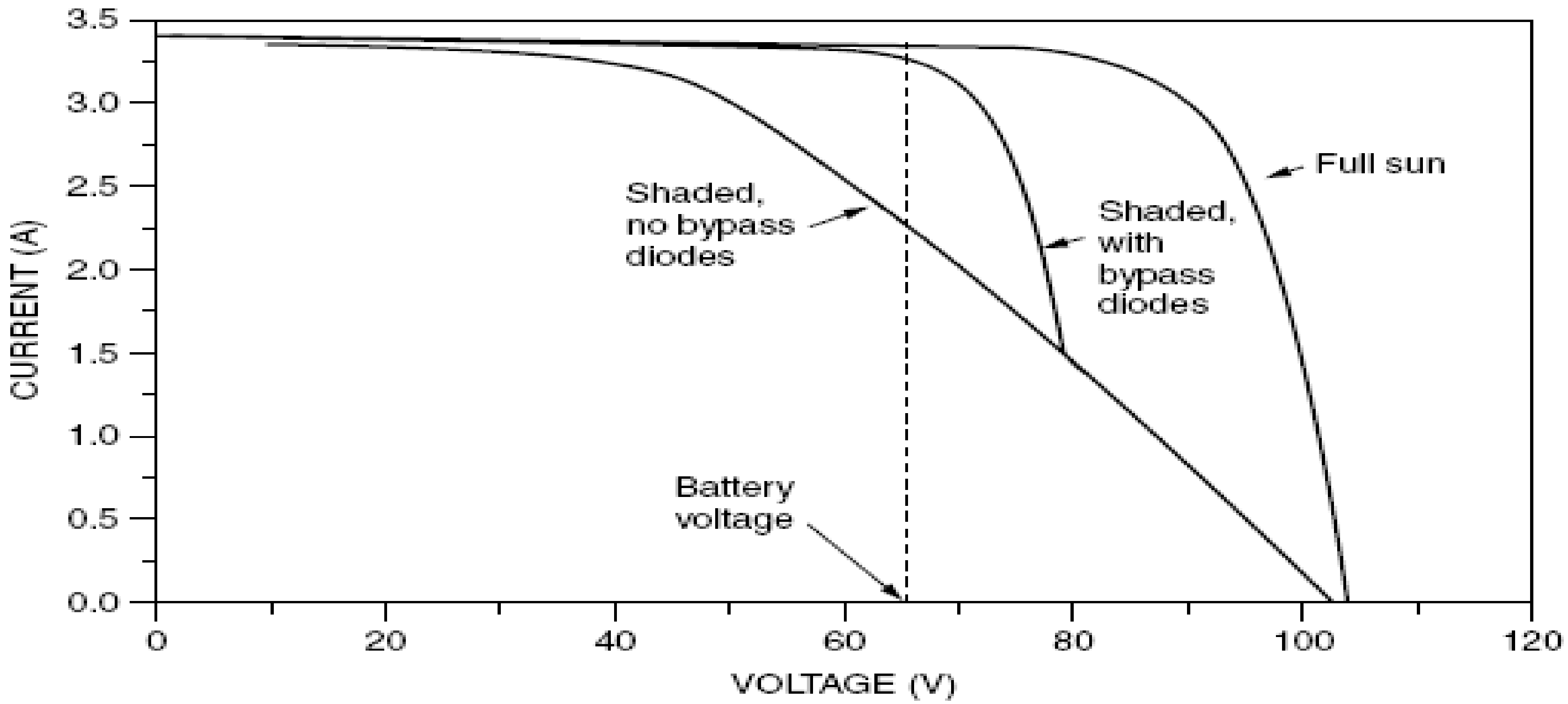
Bypass Diodes for Shade Mitigation



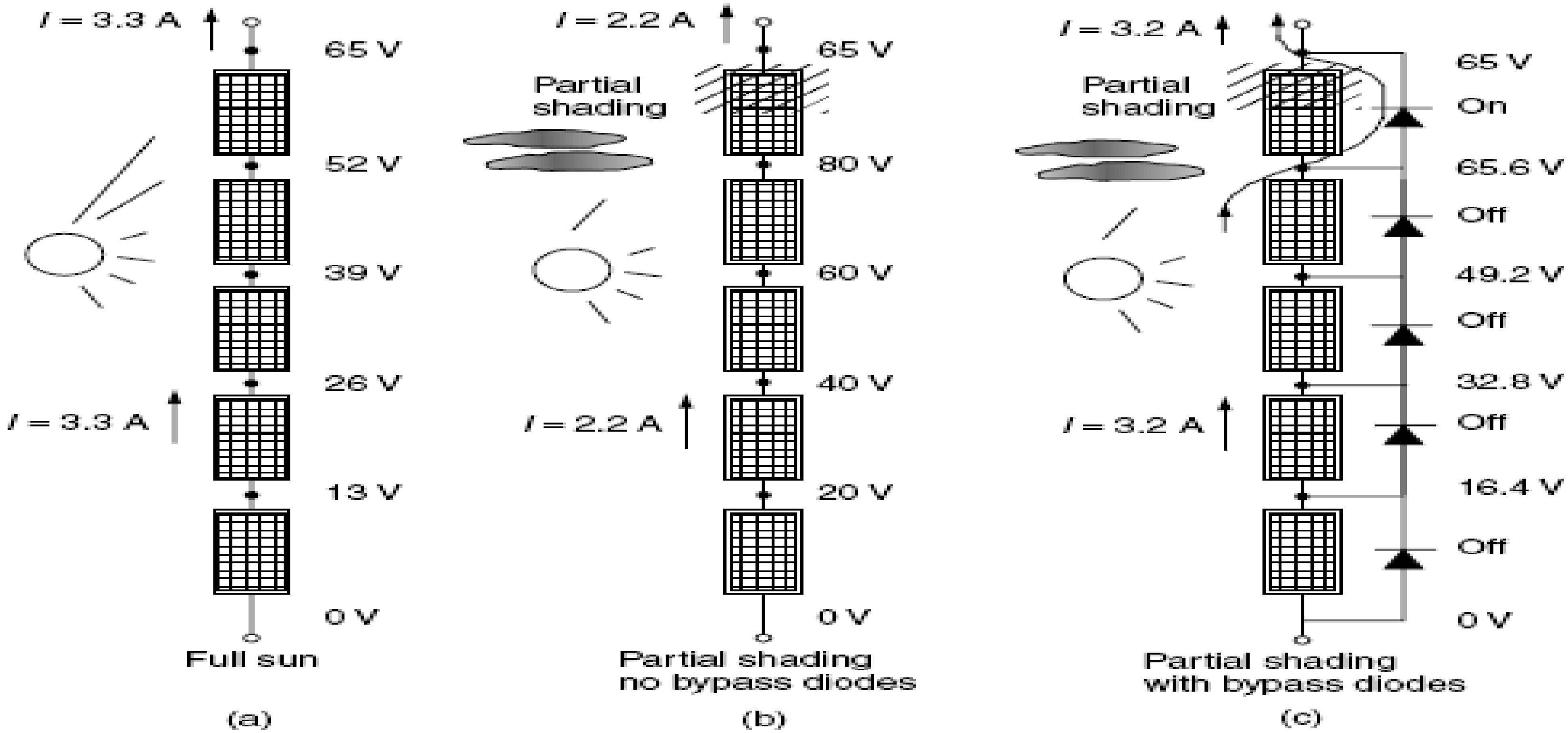
Mitigating the shade problem with a bypass diode. In the sun (a), the bypass diode is cut off and all the normal current goes through the solar cell. In shade (b), the bypass diode conducts current around the shaded cell, allowing just the diode drop of about 0.6 V to occur.

Bypass Diodes for Shade Mitigation



Impact of bypass diodes. Drawn for five modules in series delivering 65 V to a battery bank. With one module having two shaded cells, charging current drops by almost one-third when there are no bypass diodes. With the module bypass diodes there is very little drop.

Bypass Diodes for Shade Mitigation



Showing the ability of bypass diodes to mitigate shading when modules are charging a 65 V battery. Without bypass diodes, a partially shaded module constricts the current delivered to the load (b). With bypass diodes, current is diverted around the shaded module.

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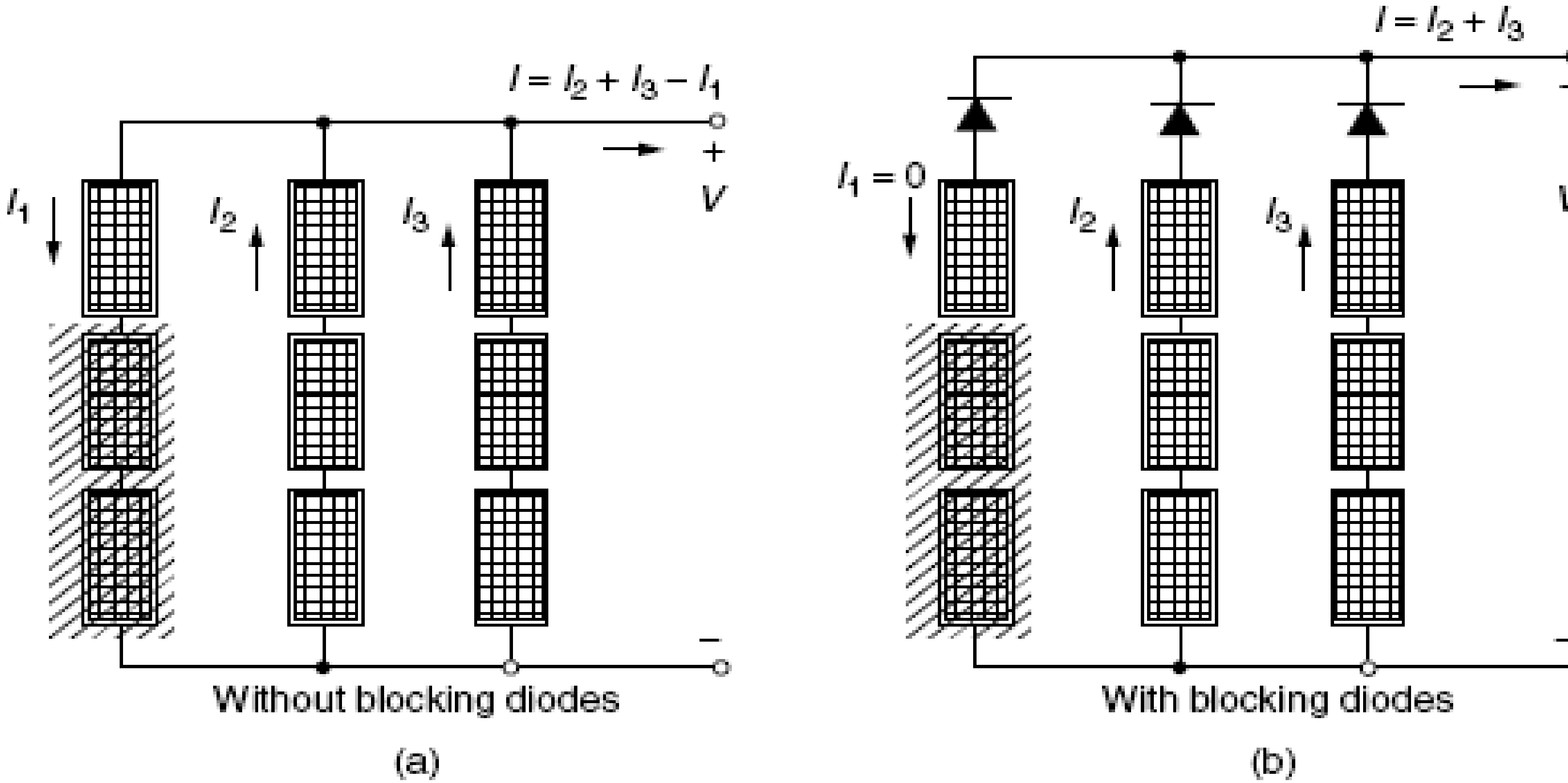
Bypass Diodes for Shade Mitigation



Blocking diodes prevent reverse current from flowing down malfunctioning or shaded strings.

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